

FINAL PROGRESS REPORT ON NASA NAG5-4494
FORMATION AND EARLY EVOLUTION OF SOLAR
AND EXTRA-SOLAR GIANT PLANETS

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This project investigates the origin of giant planets, both in the Solar System and around other stars. It is assumed that the planets form by the core accretion process: small solid particles in a disk surrounding a young star gradually coagulate into objects of a few kilometers in size, known as planetesimals, which then accumulate into solid protoplanetary cores. Once the cores have become large enough, they are able to attract gas from the surrounding disk to form the deep gaseous envelope of the giant planet. Our code simulates giant planet growth in a spherical approximation, and it has been quite successful in addressing a number of basic planetary properties. Further improvements to the code have been made to achieve a more realistic understanding of planetary formation. The computations of the models described in Pollack *et al.* (1996; *Icarus*; hereafter referred to as P96) were based on an earlier version of our code and were stopped at the onset of runaway gas accretion. Now, improved boundary conditions have been incorporated into the code to allow for hydrodynamic inflow of gas and to handle the late stages of evolution when the planet evolves at constant mass.

These changes were made to the version of the code that uses a constant accretion rate (Bodenheimer and Pollack 1986; *Icarus*) and to the version that uses a self-consistent method for calculating both the solid and gas accretion rates (P96). The equation of state has been updated to incorporate the detailed tables of Saumon, Chabrier, and Van Horn (1995; *Astrophys. J.*). The opacities were updated to include the results of Alexander and Ferguson (1994; *Astrophys. J.*). The outer boundary conditions were modified. During the accretion phase when the planet's radius is between the accretion radius and the tidal radius, we set the outer boundary at a 'modified' accretion radius, which is the point where thermal energy is enough to bring gas to the edge of the Hill sphere.

The evolution can now be followed up to an arbitrary mass, such as that of Jupiter, and for times up to several Gyr. The transition phase from an accreting planet to an isolated planet is followed. We now treat the later evolution of these planets by simulating the gradual cutoff of the gas accretion as a result of gap clearing or dissipation of the nebula. Once the gas accretion rate slows down, the outer boundary

can no longer be maintained at the ‘modified’ accretion radius, and the planet must contract to much smaller radii. Continued accretion of planetesimals during this phase is considered. Most of the planetary mass can still be considered to be in hydrostatic equilibrium, but there will be an outer, low-density region where gas will be infalling hydrodynamically from the Hill sphere down onto the planet. The outer boundary condition on the hydrostatic planet has been modified to take the infall into account. Once the infall stops, that boundary condition changes to that of a stellar photosphere, modified to include the heating from the central star, if necessary. The heating term is important for the short-period extrasolar planets.

Models simulating the formation and evolution of extrasolar planets around the stars 51 Peg, ρ CrB, and 47 UMa were computed through the phases of core accretion, rapid gas capture, and slow contraction and cooling at constant mass. The planets were assumed to have formed at their present distances from their stars; migration was not considered. In the case of 51 Peg, cases were computed at a constant solid accretion rate of $10^{-5} M_{\oplus}/\text{yr}$, and the effect of different solar nebula density values was studied. Three different cases were examined. For the standard case the density, $\rho_{\text{neb}} = 5 \times 10^{-8} \text{ g cm}^{-3}$, and temperature, $T_{\text{neb}} = 1500 \text{ K}$, of the nebula were taken from the nebula disk models of Bell et al. (1997; *Astrophys. J.*). A second case was computed with a highly reduced disk density, $\rho_{\text{neb}} = 5 \times 10^{-11} \text{ g cm}^{-3}$. This simulated an environment in which the inner disk is cleared by the effects of the stellar magnetic field, so that the tidal interaction (Lin, Bodenheimer, and Richardson 1996; *Nature*) between the protoplanet and the nebula is minimal, thereby “allowing” the protoplanet to form at 0.05 AU without concerns of orbital migration. A third case was computed with a high density of $\rho_{\text{neb}} = 5 \times 10^{-6} \text{ g cm}^{-3}$. The resulting values for the mass of the solid core ranged from 36 to 52 M_{\oplus} , increasing with decreasing density. The formation times correspondingly ranged from 3.6 to 5.2 Myr. In a further calculation in which the limiting gas accretion rate was also reduced by a factor 1000 compared with the standard rate, and $\rho_{\text{neb}} = 5 \times 10^{-11} \text{ g cm}^{-3}$, the final core mass actually turned out to be larger than the envelope mass, 89 vs. 77 M_{\oplus} . A test case was calculated (with $\rho_{\text{neb}} = 5 \times 10^{-8} \text{ g cm}^{-3}$) in which the grain opacity, which is of importance only in a thin surface layer, was reduced by a factor 10. Only small differences resulted: the core mass was reduced by 3% and the peak luminosity changed by 20%. Peak luminosities in all these cases ranged from 10^{-4} to $10^{-2} L_{\odot}$.

A similar model for the companion to ρ CrB was computed with a nebular temperature of 1200 K and a nebular density of $5 \times 10^{-8} \text{ g cm}^{-3}$. The formation time was 3.6 Myr and the peak luminosity was $\log L/L_{\odot} = -2.3$. In the case of 47 UMa, one case was calculated with a constant solid accretion rate of $10^{-5} M_{\oplus}/\text{yr}$, and two cases were computed using the version of the planetary evolution code with the self-consistent method of computing the solid and gas accretion rates. In the case of variable accretion rate, it was found that a reasonable formation time could be

obtained only if the initial surface density of solid material in the disk were set to $\approx 90 \text{ g cm}^{-2}$. For this high a density, the disk must have a high accretion rate onto its star and correspond to a relatively early evolutionary phase. The formation time for this case was 2 Myr, the luminosity peak was at $\log L/L_{\odot} = -2.1$, and the duration of the high-luminosity phase was 0.16 Myr. Results were reported at the Workshop on Brown Dwarfs and Extrasolar Planets (Bodenheimer 1998; copy of publication attached) and at the Protostars and Planets IV meeting in July 1998. The results are discussed in detail in the attached reprint from *Icarus*.

Further work was done on the later phases of the evolution of planets in short period orbits around their stars, in particular, HD 209458, Tau Boo, and Upsilon Andromedae. The calculations include tidal interaction between planets and star, and the effects of secular perturbations between the planets in a given system (the Upsilon And system has three planets). If the planet is close enough to the star, the dissipation of the stellar tidal disturbance within the planet provides a significant energy source, which causes the planet to inflate as it adjusts to a thermal equilibrium. Calculations for the three planets were carried out to determine the planetary size as a function of the assumed dissipation rate, with or without the presence of a rocky core in the planet. For a given mass planet and a given dissipation rate, a planet with a core has a smaller radius than one without. The increased radius intensifies the star-planet tidal interaction and speeds up the process of the synchronization of the planet's spin with its orbital motion and the circularization of its orbit. In the case of the planet around HD 209458, the mass and radius have been accurately determined through transit observations. The best value for the observed radius is 1.35 Jupiter radii. The dissipationless models without a core and with a core give radii of 1.20 and 1.07 Jupiter radii, respectively. A model without a core requires a dissipation rate of about 10^{-8} solar luminosities to give a radius in agreement with the observations. That is a small value but there is no obvious source for it, because the planet presumably is already in synchronous rotation and has zero eccentricity. The publication resulting from this work is attached.

Recently work has focussed on the giant planets in the solar system. Observations and modelling show that the core mass for Jupiter is in the range 0–14 earth masses, and that for Saturn is in the range 0–22 earth masses. Formation models for Jupiter actually give cores in the range 10–35 earth masses but cores in the range consistent with that in Jupiter itself correspond to formation times that are too long, far longer than deduced lifetimes of disks around young stars. The goal of the project is to determine under what conditions a Jupiter-mass planet can be formed with a core of 10 earth masses or less in a time of 10 million years or less. Calculations have been carried out which involve the study of three parameters: (1) the core mass, (2) the grain opacity in the outer envelope of the planet, and (3) the surface density of solid material in the disk.

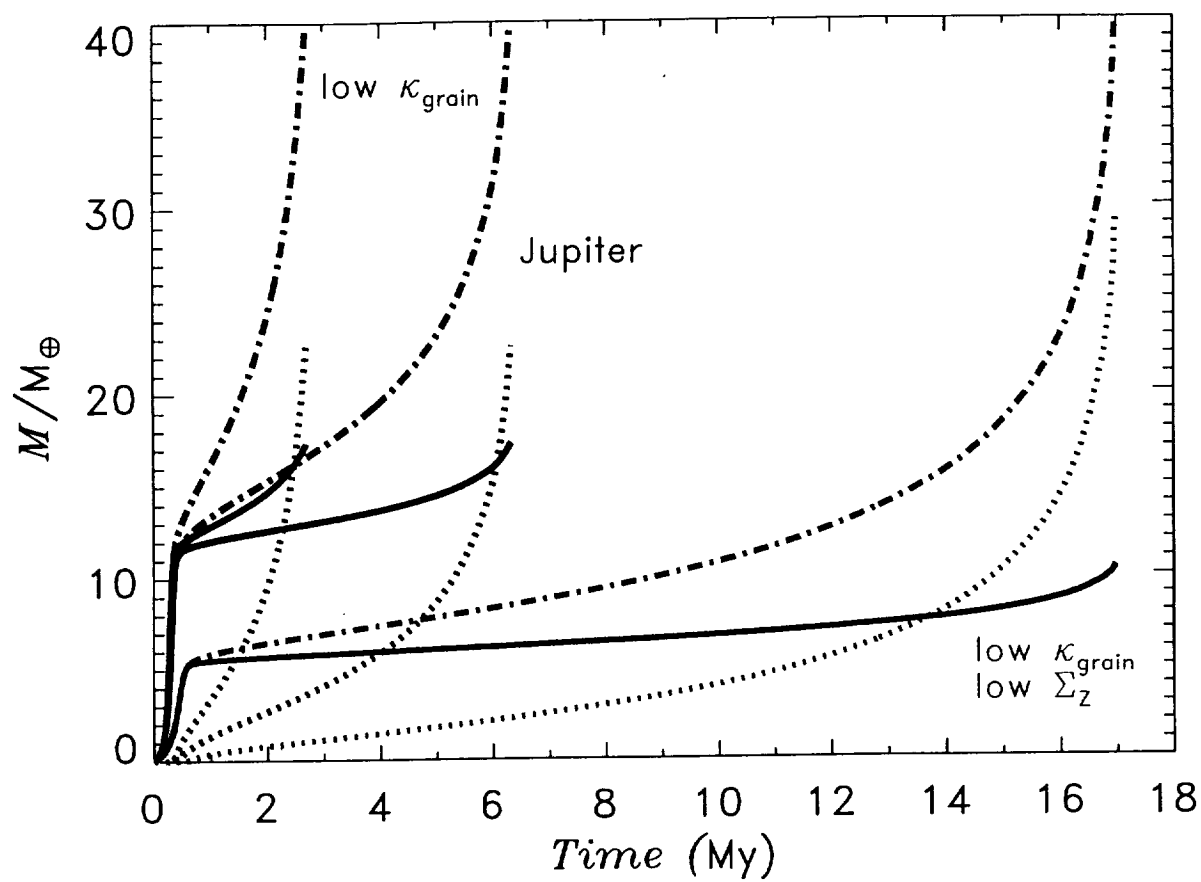
The core mass is not a parameter under the assumptions of P96, in particular, that the protoplanet builds up as an isolated embryo and there are no other embryos that compete for planetesimals. Here we relax that assumption by cutting off the solid accretion entirely once the core mass has reached some prescribed value, thereby simulating approximately the influence of neighboring embryos. The results show that depending on the cutoff mass, the evolutionary time scale can be increased or decreased.

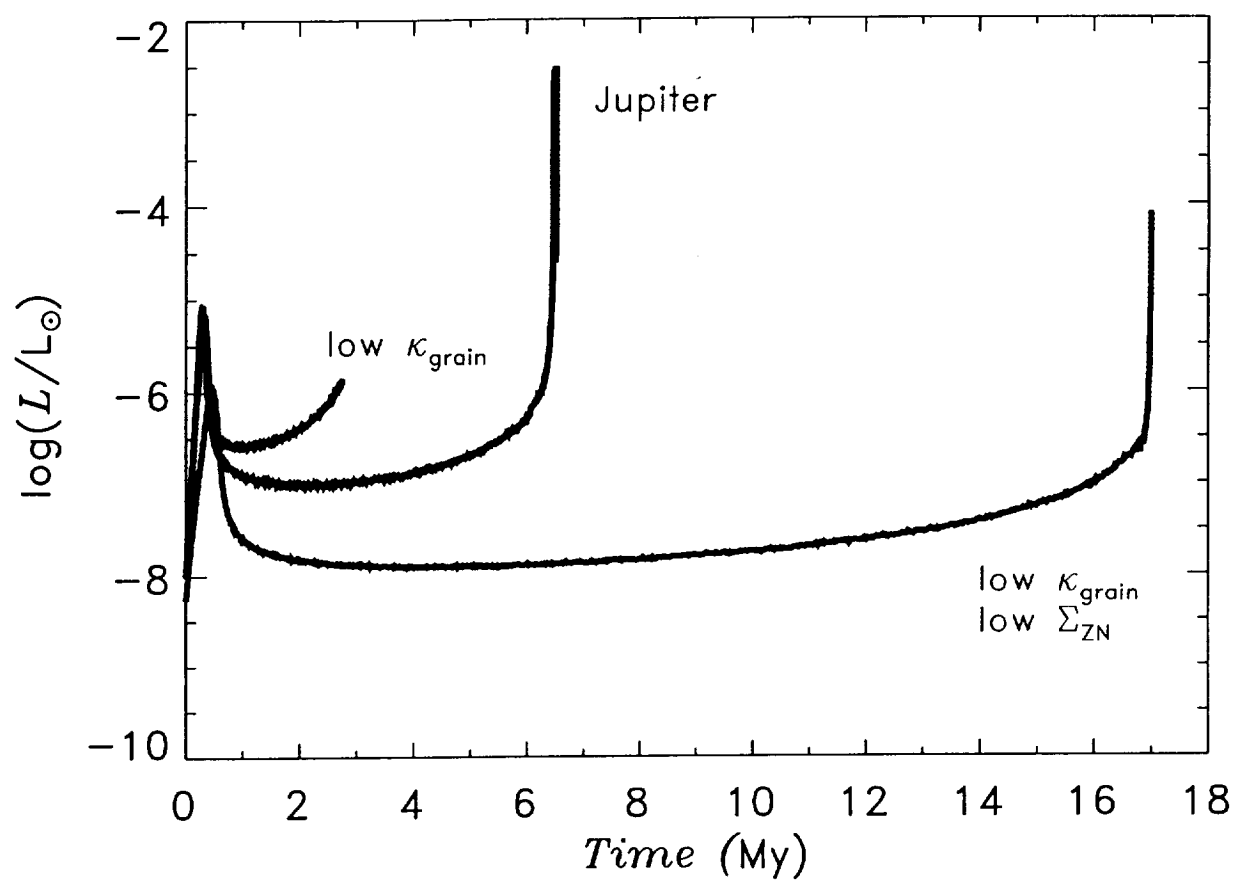
With regard to opacities, recent work in connection with this project by Podolak (2001) on the settling of small dust grains in the envelope of a protoplanet on a rather short time scale indicates that the standard opacities in models from P96 were too high in the grain region by possibly 2 to 3 orders of magnitude. Those opacities were based on a solar mixture of elements with the grains having an interstellar size distribution (with typical size less than a few tens of microns). Further discussions of the validity of applying opacities based on a solar mixture to giant planet envelopes appear in P96 and Ikoma et al. (2000: *Astrophys. J.*). The main point is that the grain properties in the material that enters a giant planet envelope over a period of several Myr have been strongly modified, with respect to interstellar grains, by settling to the midplane of the disk and by coagulation and fragmentation. Thus it is difficult to estimate the actual grain opacities, even if the grains did not settle after arriving in the outer envelope. Thus we compute a case using a solar abundance mix in the opacity, and then compare it with a model with a grain opacity reduced to 2% of the interstellar value in order to consider the implications in the formation of a gas giant formed with a decreased availability of grains in the envelope. Results from P96 indicate that variations in the opacity do not influence the final core masses, though the formation time scales are affected. Similar conclusions are reached in these more recent calculations.

The final parameter is the surface density of planetesimals. Lissauer (1987; *Icarus*) showed that this quantity must be enhanced over that in the minimum mass solar nebula (MMSN) by a factor of several, in order to get reasonable formation times. Detailed numerical simulations (P96; Ikoma et al. 2000) indicate that the factor is probably in the range 2–3. The standard value assumed here, for a protoJupiter at 5 AU, is 10 g cm^{-2} , about 3.3 times that in the MMSN. Tests are made with the value reduced to 6 g cm^{-2} . P96 show that the formation time scale is an extremely sensitive function of this parameter; reducing it has the desirable effect of decreasing the final core mass of the protoplanet but the undesirable effect of increasing the time scale.

Examples of results from a publication that is in preparation are shown in the two attached figures which show three models of the growth of Jupiter. The first gives the mass of the growing planet, in units of the earth mass, as a function of time. The curves give the mass of the gaseous component (dotted), the mass of the solid component (solid) and the total mass (dot-dashed). The red curves assume

standard interstellar grain opacities and the standard value for the solid surface density in the disk. The blue curves use a grain opacity that is 2% of interstellar values, and the standard value for the surface density. Note that acceptable formation times are obtained, but that the final core masses are a little higher than the upper limit for Jupiter. The green curves use the 2% grain opacity and a lower solid surface density (6 g cm^{-2}). Here the final core mass is acceptable (10 earth masses) but the formation time is too long. The second plot shows the luminosity radiated by the protoplanet as a function of time for the same three cases. Further calculations show it is possible to obtain both an acceptable formation time (less than 4 Myr) and an acceptable core mass (less than 10 earth masses) but only if the solid core accretion is cut off. A note to *Nature* on these recent calculations is attached.





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May 31, 2001

Dr. Joseph Boyce
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Dear Dr. Boyce:

Enclosed find one copy of the final progress report for NASA NAG5-4494. Please contact me if you need more information.

Sincerely,

A handwritten signature in cursive script that reads "Marilyn Huffman".

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Enclosure

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